Ballistic-Electron-Emission Microscopy Techniques for Nanometer-scale Characterization of Interfaces

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ABSTRACT

Semiconductor interface properties are among the most important phenomena in materials science and technology. The study of metal/semiconductor Schottky barrier interfaces has been the primary focus of a large research and development community for decades. Throughout the long history of interface investigation, the study of interface defect electronic properties have been seriously hindered by the fundamental experimental difficulty of probing subsurface structures. A new method, Ballistic-Electron-Emission Microscopy (BEEM), has been developed which not only enables spectroscopic probing of subsurface interface properties, but also, provides nanometer- resolution imaging capabilities. BEEM employs Scanning Tunneling Microscopy (STM) and a unique spatially localized ballistic electron spectroscopy method. This chapter describes BEEM methods, recent progress and important future applications.

INTRODUCTION

Semiconductor interface properties are among the most important phenomena in materials science and technology. The study of metal/semiconductor Schottky barrier interfaces has been the primary focus of a large research and development community for decades. Throughout the long history of interface investigation, the study of interface electronic properties has been seriously hindered by the fundamental experimental difficulty of probing subsurface structures. The most commonly employed methods for characterizing subsurface interface properties are applicable to Schottky barriers - the current-voltage (I-V) measurement and photoemission spectroscopy.[1] Both of these methods provide information on the Schottky barrier height of metal-semiconductor interfaces. However, both methods inherently lack the spatial resolution required to identify heterogeneous defect structures that may exist at interfaces and dominate interface properties. Further, I-V methods measure a complex weighted average of interface properties. Photoemission methods are limited primarily to the study of the early stages of interface formation. The surface sensitivity of photoemission precludes the investigation of fully formed interfaces where perhaps tens of monolayers of metal or semiconductor are deposited on a substrate.

Research on Schottky barriers has relied on electronic methods for measurement of the interface barrier height. However, as will be seen below, the measurement of Schottky barrier height alone is insufficient for understanding interface properties. In fact, the measurement of interface carrier transport is found to be of primary importance in determining the electronic properties of the Schottky barrier. Interface barrier height, interface carrier transport, and interface band structure properties must all be measured to proceed with a study of interface formation and properties.

Transport properties of carriers in metals, in semiconductors and through interfaces have also been important in both fundamental condensed matter physics and in device technology. The experimental investigation of carrier transport by has been limited to conventional conductivity measurements which probe carrier transport at the Fermi energy. Recently, internal photoemission and ballistic carrier spectroscopies have provided methods for extracting detailed transport parameters for a wide range of systems. However, many of the most fundamental questions regarding the nature of carrier transport and scattering are still unanswered. In particular, the relative contributions of elastic and inelastic processes in scattering have not been directly probed. Further, experimental investigations have historically lacked an energy-resolved probe of scattering. Progress in this area is of increasing importance due to rapid advances in device technology based on ballistic carrier transport for transistor amplifiers and novel radiation detectors.

A new method, ballistic-electron-emission microscopy (BEEM)[2], has been developed which not only enables probing of subsurface interface properties, but also provides nanometer-resolution imaging capabilities. BEEM employs Scanning Tunneling Microscopy (STM)[3] and a unique spatially localized ballistic electron spectroscopy method. BEEM enables spectroscopic imaging of subsurface interface electronic structure including interface carrier transport and band structure.[4] In addition, BEEM methods have been developed for direct investigation of carrier transport and scattering. BEEM provides the first wide energy-range (0.1 - 10eV) spectroscopies of electron and hole scattering with direct detection of carriers created by scattering.

EXPERIMENTAL

The BEEM method employs STM techniques combined with unique ballistic carrier spectroscopy methods to enable probing of subsurface interface structures. Elastic tunneling of electrons between the STM tunnel tip and a structure under study results in the injection of ballistic electrons into the structure. Typical ballistic electron attenuation lengths in metals are greater than 100 Å. The injected ballistic electrons propagate through the structure, therefore, and probe subsurface properties. Figure 1 shows energy band diagrams for application of the BEEM method to a metal-semiconductor heterostructure. In this three-terminal configuration, electrodes are attached to the STM tunnel tip, the metal film (base), and to the semiconductor collector. For base-tip bias, V, less than the Schottky barrier height, V_b, there will be no collector current, since the ballistic electron distribution has insufficient energy to surmount the energy barrier. However, if V exceeds V_b, as shown in Figure 1b, a fraction of the ballistic electrons may propagate through the interface and into the collector where the current is detected. The actual collected current depends on the base and base-collector interface properties, including electron attenuation length in the base, the SB height, defect structure at the interface, and quantum-mechanical reflection at the interface. Spectroscopic analysis of the collector current will, therefore, yield direct information on these critical interface properties.

BEEM imaging may be accomplished while scanning the STM tunnel tip over the heterojunction upper surface (vacuum interface) under feedback control of tunnel current. The tunnel bias is set at a value greater than the threshold voltage, V_b, for observing ballistic electron current at the collector. The collector current is measured while scanning the tip so as to produce simultaneous images of both the upper surface topography and subsurface electronic structure. BEEM spectroscopy measurements on Au/Si(100) Schottky diode structures for a range of Au electrode thickness yield an exponential decay of ballistic electron transmission probability with film thickness characterized by a mean-free-path of 128 ± 10 Å.[5] For example, a variation in Au base electrode thickness as large as 100Å yields only a factor of 2 variation in collected current. This demonstrates that for a Au/semiconductor structure, the measured ballistic electron collector current is insensitive to variations in the thickness of the metal base electrode and is dominated by variations in electron transmission due to spatial variations in interface structure.

BEEM images of subsurface properties may also be acquired by measuring complete BEEM spectra at each image location. From these spectra an image may then be formed of various properties including SB height.

BEEM APPLICATIONS TO SCHOTTKY BARRIERS

The development of metal-semiconductor Schottky barrier interface physics has proceeded for over fifty years. Particular attention has been directed to the complex and technologically important metal-GaAs interface.[1] Investigation of the important Au-GaAs Schottky barrier has been directed to both the Au-GaAs(110) and Au-GaAs(100) systems. For all Schottky barrier systems the preparation of the semiconductor surface prior to metal deposition is a critical step of interface formation. The preparation of the Au-GaAs(110) interface simply requires the cleaving of a melt-grown GaAs crystal to expose the (110) surface followed by the deposition of Au. Both the GaAs(110) surface and metal-GaAs(110) Schottky barriers have been extensively characterized by many methods. However, the fundamental step of high-quality GaAs thin-film epitaxy required for many device applications may be performed on the (100) surface, not on the (110) surface. For this reason, the understanding of Schottky barrier interface formation on the GaAs(100) surface is of central importance to device physics and technology. Progress in this area, however, is hindered by the inherent complexity of the (100) surface. In contrast to the (110) surface, the (100) surface is usually prepared on mechanically-polished surfaces of melt-grown GaAs. The GaAs(100) surface treatments for Schottky barrier formation have included chemical etching and chemical etching and annealing.[1] The GaAs(100) surfaces prepared in this way show a rich set of reconstructions which vary with surface treatment. Investigation of Au/GaAs interfaces provides an example of the unique capabilities of BEEM.[5]

Schottky barrier diode structures were prepared for this investigation using a unique processing facility. A Riber 2300 MBE system was linked by an ultra-high vacuum (UHV) transfer system to a nitrogen gas-purged "glove-box" chamber and a UHV chamber equipped with a metal deposition system and substrate shadow masking. This combined facility enables semiconductor substrates to be prepared by chemical etching techniques in a controlled-atmosphere environment. Substrates may be then introduced directly from the nitrogen gas environment into the MBE system or into the metal deposition system. In addition, a unique in-situ interface formation method is enabled by direct UHV transfer between the MBE and metal deposition chamber.

Figure 2 shows STM topographic and BEEM images for a Au/GaAs(100) interface prepared by MBE deposition, and surface chemical etching prior to metal deposition. The greater fraction of the BEEM image area shows regions of zero detectable ballistic electron current, less than 0.1 pA. Small regions, comprising less than 10 percent of the image area, transmit ballistic electrons at currents larger than 10pA. The scale of the heterogeneity is small; substantial changes in measured ballistic electron current occur on the nanometer scale. The dramatic spatial variation in ballistic electron current observed may not be explained by film thickness variation. (Based on the measured mean-free-path for ballistic electrons in Au, a film thickness variation of greater than 600Å would be required to explain the large current variation observed.) The BEEM image displays, therefore, defective interfacial regions. The defects may be created at the substrate surface prior to metal deposition, after metal deposition during subsequent diffusion between metal and semiconductor electrodes, or are related to bulk defects. (Surface contamination has been ruled out as a source of defect formation since x-ray photoemission spectroscopy methods were used to show that the chemically etched GaAs surfaces were uncontaminated by surface oxide prior to Au deposition.[5]) The presence of the defects are expected to have profound impact on the understanding of Au/GaAs(100) interface formation and on the performance of Au/GaAs(100) Schottky barrier device structures.[1]

BEEM has been applied to identify the origin of the Au/GaAs(100) interface defect structure. An investigation combining MBE, photoemission and BEEM techniques has identified interdiffusion of the Au and GaAs electrodes as the origin of interface defects.[5] MBE techniques were applied to prepare a unique heterostructure as a substrate for an ideal Schottky barrier. The heterostructure, grown on an n-type GaAs(100) substrate, includes an n-type GaAs(100) buffer layer, terminated by a single unit cell (5.6 Å thickness) AlAs buffer layer, and covered with a UHV-deposited (100 Å thickness) Au layer. The Au layer was deposited *in-situ,* after direct UHV transfer from the MBE chamber. The combination of BEEM and photoemission investigation shows that the AlAs layer forms a chemical diffusion barrier against transport of Ga and As into the Au metal layer.[5] It can be seen immediately in Figure 3 that BEEM reveals a dramatically reduced defect density for the Au/AlAs/GaAs(100) Schottky barrier. BEEM has provided an essential tool, therefore, for the discovery, identification of interface defects, and the development of an ideal interface structure.

BEEM SPECTROSCOPY

BEEM electron spectroscopy has enabled the direct investigation of many n-type Schottky barrier systems. An important example is the spectroscopy of interface band structure. Here BEEM has been employed to directly measure the energy positions of the zone-centered and satellite conduction band minima of GaAs.[4] This capability is currently being extended to include an investigation of the development of electron band structure in thin heterostructure layers. BEEM methods may also be applied to p-type Schottky barriers. Here the STM tunnel tip is biased positive with respect to the sample structure under study, and electrons tunnel from filled states below the Fermi level in the sample to empty states in the tip. This creates vacancies (holes) in the sample conduction band. As shown in Figure 1c, holes in the sample are available for transport through the buried interface of the Schottky barrier. Several important Schottky barrier systems, including Au/Si, Au/GaAs(100), and $CoSi_2$/Si have been investigated with hole spectroscopy.[6,7]

BEEM methods also allow the direct measurement of carrier scattering for both electrons and holes.[8] Scattering spectroscopy, shown in Figure 4, is based on the injection of nonequilibrium carriers into a heterostructure, followed by the direct detection of carriers created by scattering. The investigation of electron scattering in a thin metal base layer is accomplished with a Schottky barrier structure prepared on a p-type substrate as shown in Figure 4a. For this system, incident electrons scatter and produce an electron-hole pair which continues to propagate. The p-type collector prevents the recovery both of electrons from the incident flux and those created by scattering. A preliminary consideration of this experiment would indicate that a collector current would not be observed. However, holes created by pair-production during scattering are allowed to propagate into the collector for hole energies less than the (valence band to Fermi energy) Schottky barrier. The Schottky barrier provides, therefore, an energy filter which enables a spectroscopy of carrier scattering. A distinguishing feature of this experiment is that the sign of the collected current due to holes is *opposite* from the injected electron tunnel current. The complementary experiment for hole scattering involves the decay of a nonequilibrium hole by pair creation and the detection of the excited electron in an n-type collector.[8]

In contrast to conventional transport measurements which measure only the attenuation of an unscattered carrier flux, this unique method measures only scattering events. In addition, while conventional measurements indirectly measure scattering, the BEEM method resolves the carriers created by the scattering process from unscattered carriers. Applications for this new method exist in many areas of transport physics. The unique capabilities of an energy-resolved probe combined with detection of scattering products are important for determining the role of various scattering processes on transport in a material or structure. The nature of the BEEM technique also allows spectra to be spatially resolved with nanometer resolution, thereby revealing the contributions of defects to scattering. This method is also applicable to a wide variety of structures comprised of metals, semiconductors, and thin insulating barriers.

CONCLUSION

BEEM provides the first nanometer-scale resolution probe of subsurface interfaces. Applications of BEEM include a wide variety of material and interface investigations. Precision measurements of Schottky barrier formation and interface transport using a powerful UHV BEEM apparatus have been demonstrated by Prietsch and Ludeke for several important systems.[9] Fernandez et al. have shown that local interface modification may be performed by BEEM. Using this BEEM method the interface modification may also be directly imaged.[10] Recent theoretical investigation of Henderson et al. indicates that BEEM methods will provide a unique and powerful probe for investigation of heterostructure properties.[11] The important topic of interface carrier transport is being investigated with BEEM by Schowalter and Lee. Anomalous results in BEEM spectroscopy investigations have revealed that the understanding of carrier transport in metals and through interfaces is lacking.[12] A variety of novel material systems have been investigated with BEEM techniques by Fowell et al.[13] Finally, important contributions to the understanding of interface transport and BEEM have been made by the theoretical work of Stiles and Hamann.[14]

The diversity of future BEEM applications is demonstrated by the wide range of these current research activities. The rapid growth of this area indicates that many exciting BEEM applications and techniques will be important in condensed matter physics and materials science.

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BIBLIOGRAPHY

1. For an extensive review see Brillson, L J 1982 Schottky barrier interfaces *Surf Sci. Rep.* 2, 123-220.
2. Kaiser W J, Bell L D 1988 Direct investigation of subsurface interface electronic structure by ballistic electron emission microscopy, *Phys. Rev. Lett.* **60,** 1406-9
3. Binnig G, Rohrer H, Gerber Ch, Weibel E 1982 Scanning tunneling microscopy, *Phys. Rev. Lett.* **49**, 57-604.
4. Bell L D, Kaiser W J 1988 Observation of interface band structure by ballistic-electron-emission microscopy, *Phys. Rev. Lett.* **61**, 2368-71
5. Hecht M H, Bell L D, Kaiser W J, Grunthaner F J 1989 Ballistic-electron-emission microscopy of Au/GaAs interfaces *J. Vac. Sci. Technol.* **B7**, 945-8.
6. Hecht M H, Bell L D, Kaiser W J, Davis L C 1990 Ballistic hole spectroscopy of interfaces *Phy. Rev. B* **42,** 7663-7.
7. Kaiser W J, Hecht M H, Fathauer R W, Bell L D, Lee E Y. 1991 Ballistic carrier spectroscopy of $CoSi_2$/Si interfaces *Physical Review B* **44.**
8. Bell L D, Hecht M H, Kaiser W J, Davis L C 1990 Direct spectroscopy of carrier scattering *Physical Review Letters* **64,** 2679-81
9. Prietsch M, Ludeke R 1991 Ballistic electron emission microscopy and spectroscopy of GaP(110)-metal interfaces *Physical Review Letters* **66,** 2511-14
10. Fernandez A, Hallen H D, Huang T, Buhrman R A, Silcox J, 1991 Ballistic electron studies and modification of the Au/Si interface *Applied Phys. Lett.* **57**, 2826-9
11. Henderson G N, Gaylord T K, Glytsis E N, First P N, Kaiser W J, 1991 Ballistic electron emission testing of semiconductor heterostructures *Solid State Comm.* **80** 591-4
12. Schowalter L J, Lee E Y 1991 Role of elastic scattering in ballistic-electron-emission microscopy of Au/Si(001) and Au/Si(111) interfaces **43,** 9308-11
13. Fowell A E, Williams R H, Richardson B E, Cafolla A A, Westwood D I, Woolf D A 581

studies of Au-CdTe and Au-GaAs interfaces and band structure *J. Vac. Sci. Technol.* **B9**, 581-4

14. Stiles M D, Hamann D R 1991 Theory of ballistic-electron-emission spectroscopy of $NiSi_2$/Si(111) interfaces *Physical Review Letters* **66**, 3179-81

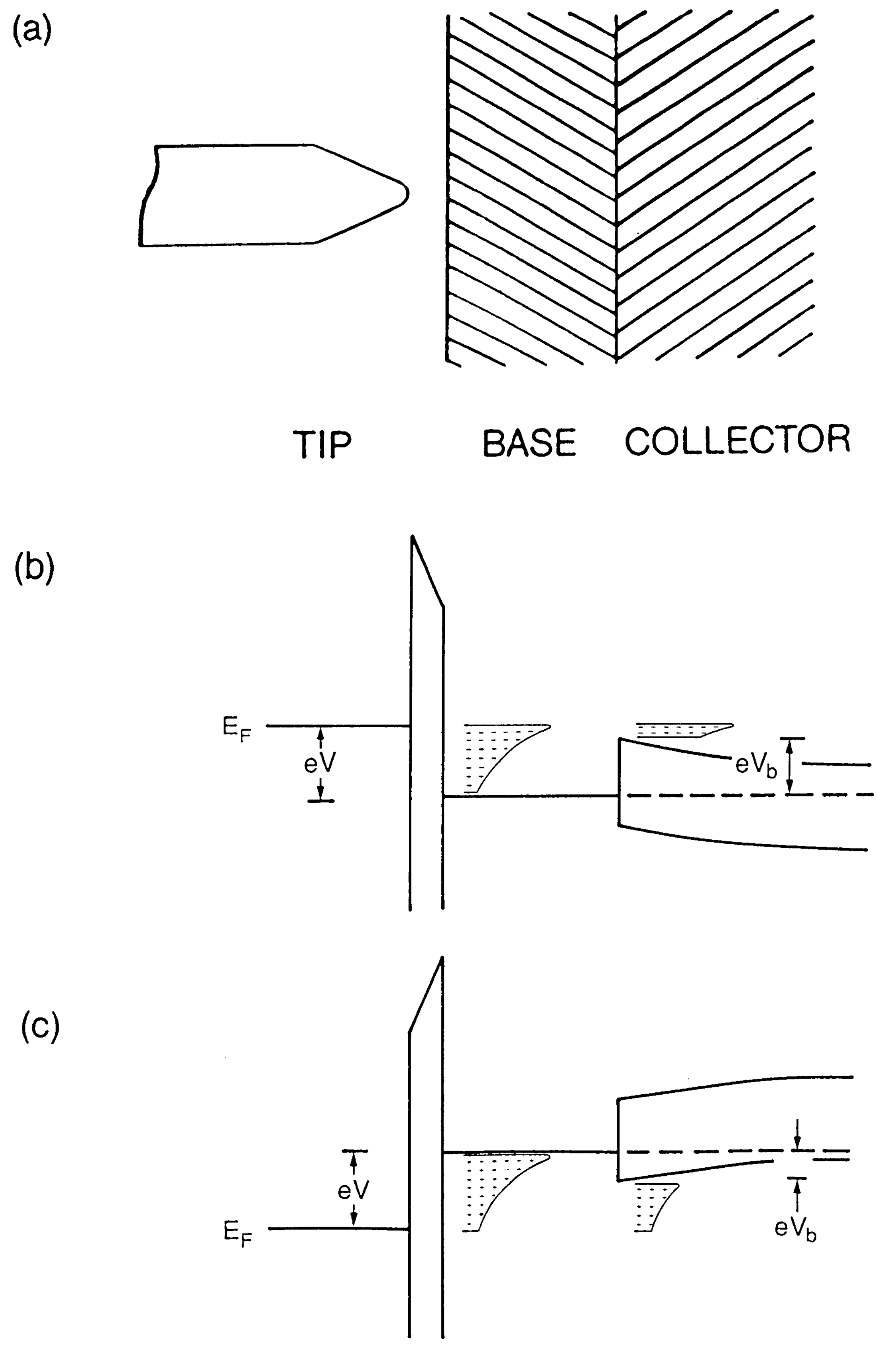
FIGURE CAPTIONS

Figure 1. The three-terminal BEEM configuration applied to a metal-semiconductor Schottky barrier interface. The tunnel tip is separated by a vacuum barrier from the metal base electrode. Terminals are applied to the tunnel tip, metal base, and semiconductor collector. The collector current, I_c, is measured between base and collector. (b) The energy band diagram for zero tunnel bias, $V = 0$. (c) The energy band diagram for tunnel bias greater than the barrier voltage, $eV > eV_b$.

Figure 2. STM topographic and BEEM images of a Au/GaAs(100) Schottky barrier interface prepared by MBE-deposition and chemical etching without air exposure before metal deposition. The STM (upper) and BEEM images (lower) were acquired simultaneously. Both images display a 510 x 310 $Å^2$ area. (upper) STM topographic image. Surface height range from minimum to maximum is 70 Å. (lower) BEEM image obtained at a tunnel bias $V = 1.5$ V and $I_t = 1.0$ nA. The local value of I_c is represented by topographic altitude. The dark regions of the image are regions of zero detectable collector current. The maximum value of I_c is 14 pA.

Figure 3. STM topographic and BEEM images of a Au/AlAs/GaAs(100) Schottky barrier interface prepared by MBE-deposition and metal deposition in UHV. The STM (upper) and BEEM images (lower) were acquired simultaneously. Both images display a 510 x 310 $Å^2$ area. (upper) STM topographic image. Surface height range from minimum to maximum is 24 Å. (lower) BEEM image obtained at a tunnel bias $V = 1.5$ V and $I_t = 1.0$ nA. The local value of I_c is represented by topographic altitude. The average value of the collector current in this image is 2.0 pA with a standard deviation in the distribution of currents of 0.7 pA.

Figure 4. (a) The electronic structure for BEEM spectroscopy of electron scattering with a p-type collector. The hole created below the Fermi energy is shown propagating through the interface and occupying a state in the semiconductor collector valence band. The Schottky barrier height is labeled as eV_{bp}. (b) Comparison of experimental BEEM spectroscopy results for hole ballistic transport with electron scattering. These spectra for the Au/Si(100) interface structure were measured at a tunnel current of 1 nA. The experimental ballistic hole transmission spectrum is obtained for positive tip bias. The Schottky barrier height, eV_{bp} (see Figure 2a), extracted from this spectrum is 0.35 eV. The experimental electron scattering spectrum (dots) for negative tip bias is compared with theory (solid line). A magnified plot of the electron scattering spectrum is also shown.



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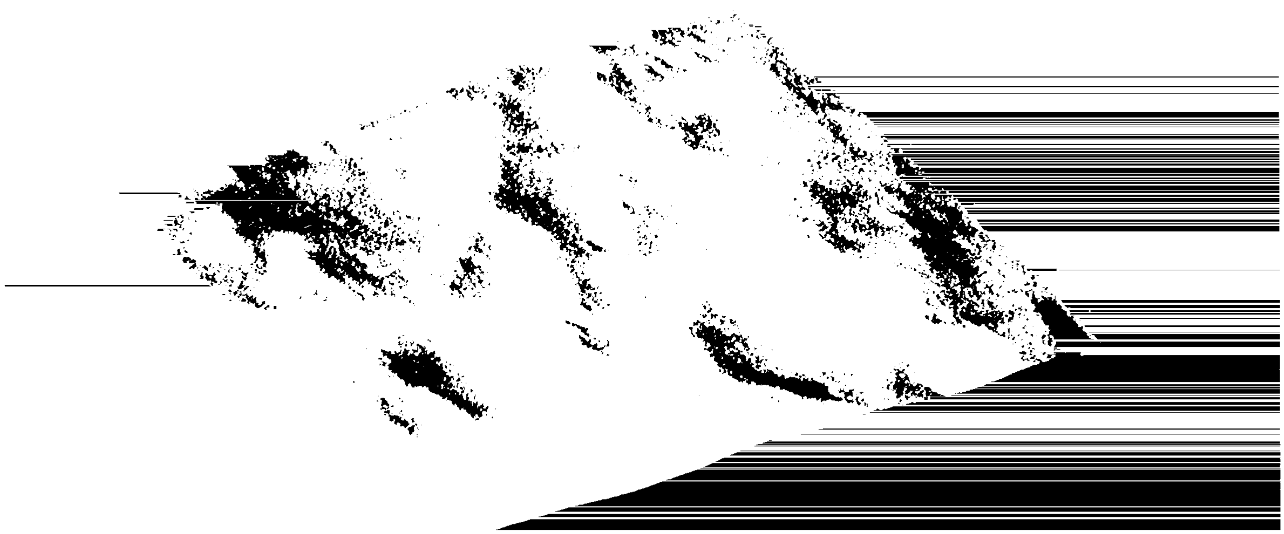

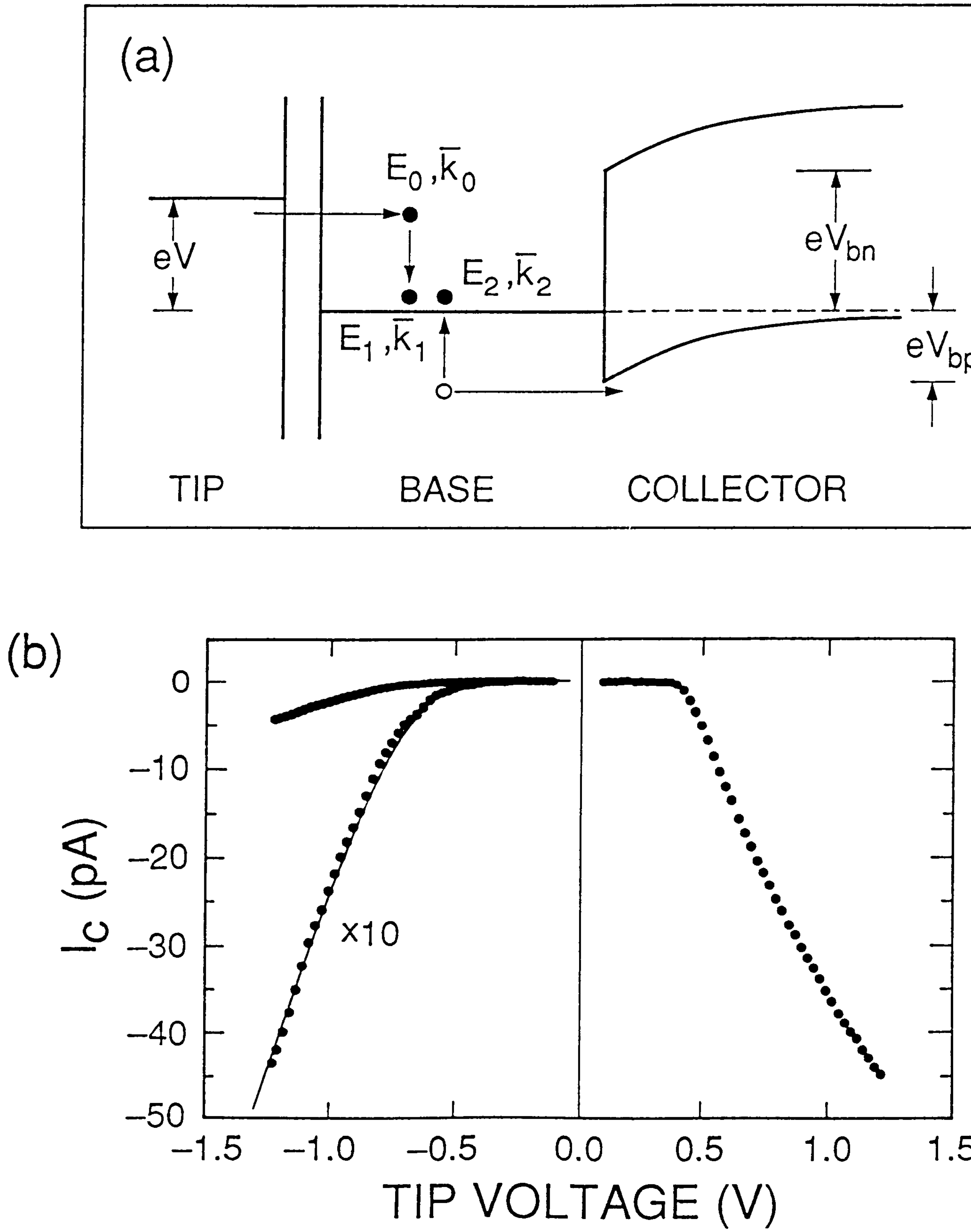
(a)
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